October 14, 2005

Hon. John J. Duncan, Jr.
Chairman
Subcommittee on Water Resources
Committee on Transportation and Infrastructure
U.S. House of Representatives
Washington, D.C. 20515

Testimony of Roy K. Dokka, Ph.D. Regarding the Effect of Subsidence on Flood Protection Options and Water Resources Planning in the Gulf Coast

EXECUTIVE SUMMARY

A major factor behind the destruction of the gulf coast by Hurricanes Katrina and Rita was the on-going sinking of the land, aka, subsidence. Subsidence is generally caused by unrelenting natural processes but has been augmented locally due to poorly managed groundwater withdrawal and/or drainage projects. Coastal Louisiana has subsided between ~2 and 4 feet since 1950. Subsidence is not restricted to the coast as previous thought but extends inland area for hundreds of miles, especially along the Mississippi River valley. As the land has sunk, so have our levees defenses, evacuation roads, and wetlands. Besides the making the coast increasing the vulnerability of coastal communities to storm surge, subsidence has ruined the official system of vertical control benchmarks we use to determine elevation in Louisiana, Mississippi, Texas, and portions of Arkansas, and Alabama. Examples of the implications of an inaccurate vertical control system:

- ✓ The USACE and levee districts cannot at present plan and build new or augment hurricane protection levees to proper elevations; The levees are as much 2 feet lower than they were designed;
- ✓ NOAA/National Hurricane Center cannot at present produce accurate storm surge models of the gulf coast;
- ✓ FEMA cannot make accurate flood insurance rate maps; areas mapped outside the flood zone may be in the flood zone.
- ✓ State and federal highways are being built below their design heights. They may not be able serve as escape routes during storms and will likely degrade more quickly due the elements.
- ✓ Consumers cannot get accurate elevations on home slabs for insurance purposes.

Subsidence measurements of the region published in 2004 by NOAA (Shinkle and Dokka, 2004) shows that the entire coast, as well as adjoining upland areas, have been sinking. These new authoritative data call into question the scientific causations underpinning mitigation strategies designed to restore Louisiana's coastal wetlands. These strategies were predicated on the belief that only the wetlands were changing. Wetland-centric strategies, however, cannot help protect the subsiding land areas of the coast where people live and work. Higher levees that span the entire coast from Texas to Alabama are needed now. The regional vertical control network needs to be updated now to support planning and levee construction.

PURPOSE AND SCOPE

The purpose of this report is to provide the Committee with information regarding the nature and societal implications of the ongoing subsidence affecting the states bordering the Gulf of Mexico. The report attempts to distill for the Committee the "state of the science" of subsidence that has been obtained from previous geological, geophysical, and geodetic studies. The analysis also draws heavily from a report written by Mr. Kurt Shinkle and myself and issued in 2004 by the National Oceanic and Atmospheric Administration, U.S. Department of Commerce. The report, *NOAA Technical Report 50*, is available at www.ngs.noaa.gov, and documents land movements that have occurred over the past fifty years using the most precise and reliable data available. Thematically, my testimony covers issues regarding:

- The definition of subsidence;
- The causes of subsidence;
- The detection and measurement of modern subsidence occurring in the south-central United States (Louisiana, Mississippi, Alabama, Texas and Florida);
- The prognosis for continued subsidence in the near future;
- The practical implications of subsidence for the future of the gulf coast;
- Comments regarding how Society can effectively cope with subsidence.

BACKGROUND

Subsidence: Definition

The word, subsidence, as used in this case, can be defined as: ***the lowering of the surface of the Earth with respect to a datum*** (Shinkle and Dokka, 2004). Lowering of the land surface implies that a change occurred in height with respect to a reference point or datum over a period of time. Thus, to measure subsidence at some point on the Earth requires:

- An appropriate measurement tool sensitive to resolve height change. The tool, e.g., ruler, defines the precision of the measurement.
- A datum with which to reference measurements. A datum is a point, line, or surface that serves as a reference. The quality of the datum is the critical factor in determining the accuracy of a measurement. If the datum is poorly chosen, then the accuracy of related measurements will be poor. It is the known point that allows unknown points to become known. An example of a precise datums is:
  - ✓ North American Vertical Datum of 1988 (NAVD88) – currently official vertical datum of the United States of America. It replaced National Geodetic Vertical Datum of 1929 (NGVD29). NAVD88 is a network of over 500,000 points spread over the continent whose exact spatial topology was known as of 1988. It is an orthometric datum. Several federal agencies still use the out-dated datum.

If measurements are made without reference to a proper datum, then all measurements are unknown. An example of an inappropriate datum for the measurement of subsidence is sea level. In 1988, the United States of America officially abandoned the use of sea level as the official reference for heights and elevations. It did so because it became known that sea level is not at the same elevation everywhere and that its elevation changes globally over time.

THE CAUSES OF SUBSIDENCE

A 190 Million Year History of Subsidence

Subsidence is nothing new to the south-central United States. It has been occurring in south Louisiana and the entire Gulf of Mexico basin since the Jurassic Period, the time of the great dinosaurs some 190 million years ago. In support of the exploration of oil and gas, the region is the most heavily studied geologic province on Earth. It is widely known that the Gulf of Mexico basin (Fig. 1) contains an aggregate thickness of rock layers of nearly 60,000 feet (10 miles). To put this into perspective, this massive stack of sedimentary rock layers is equal to the layers of rock exposed in the Grand Canyon multiplied by 10! Most of these sediments consist of sedimentary rock deposited at or near (less than 100 feet water depth) sea level. How then did such a great thickness of sediments of shallow origin accumulate? It is again widely understood by geologists that the crust of the Earth has been shouldered aside over time by the weight of sediments deposited at the edge of the continent by the Mississippi River and other rivers on the gulf coast, and their ancestors.

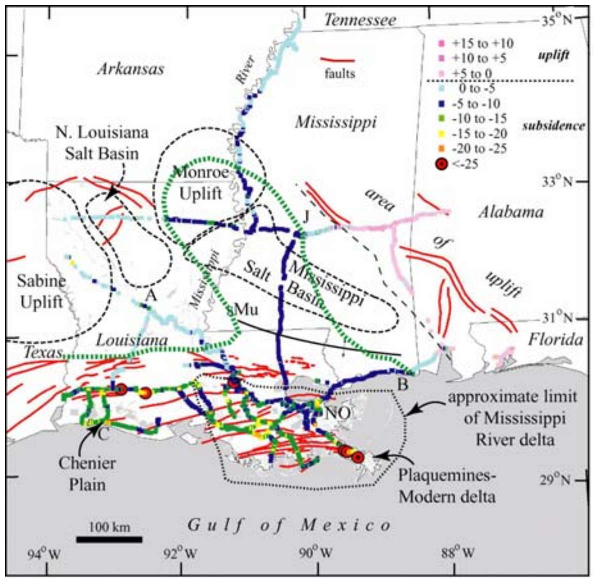
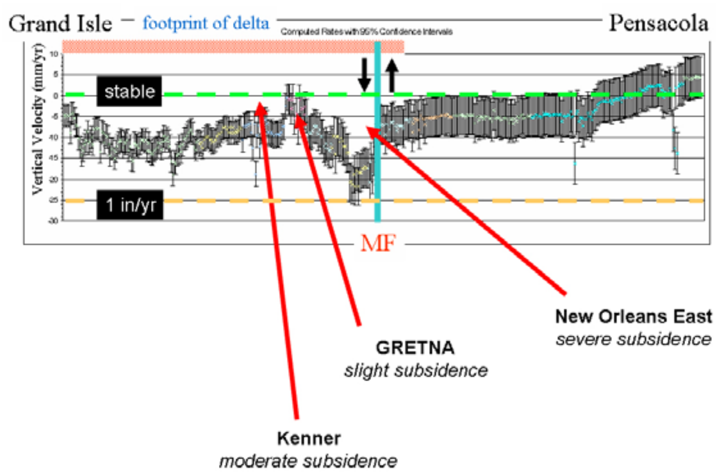


Figure 1. Tectonic map of states bordering the Gulf of Mexico. Colored point symbols are benchmark velocities determined by Shinkle and Dokka (2004). All rates are related to NAVD88. Rates are latest values from a given area and do not represent a single time interval. See Figure 2 for examples of changes in rates over time. Fig. 2 section endpoints: A, Alexandria; B, Biloxi; C, Creole; J, Jackson; NO, New Orleans.

An enormous volume of debris eroded from the Rocky Mountains and the Appalachians is carried by the waters of the mighty Mississippi River (and other rivers) each year. Upon entering the Gulf of Mexico, the river slows to a stop and the sediments come to rest forming the Mississippi River delta. This massive pile of sediments at the edge of the continent has two characteristics. First, its colossal weight has depressed, and continues to depress the Earth's crust and mantle. The sediments push down the edge of the continent just as a diver's weight causes a diving board to bend downward beneath his or her feet. Second, the pile of sediment is weak and unable to support itself laterally; it is wholly unsupported to the south. Over time, large tracts of the unstable pile have slumped southward along south dipping or sloping faults. Piling such massive loads of sediments have also lead to another geologic phenomena that Louisiana is especially famous, the mobilization of underground salt (Fig. 1).

The modern landscape of southeast Louisiana was created following the last ice age and is built upon a coastal delta created by the Mississippi River during the past 8,000 years (Fig. 1). Numerous studies have demonstrated that both natural and anthropomorphic processes have played roles in the lowering of the land surface relative to sea level since the last sea level low stand. Prior to human-induced change in the amount of sediment carried by the Mississippi River and to construction of flood control levees by individuals and local, state, and federal governments, subsidence was offset naturally to a large degree by deposition of river sediments during floods and *in situ* organic sediment production in marshes. Both of these changes were in large part due to direct actions of the US Army Corps of Engineers (USACE) as requested by Congress. It should be pointed out that if the USACE had not finished building the regional system of levees, the Mississippi River would have remained unreliable for commerce to and from the heartland of the USA and south Louisiana would have continued to be ravaged by yearly floods.

a)



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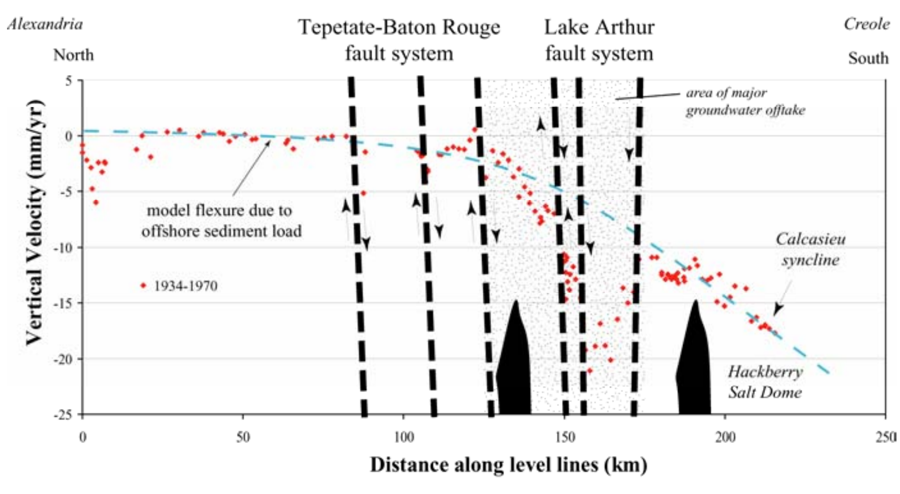

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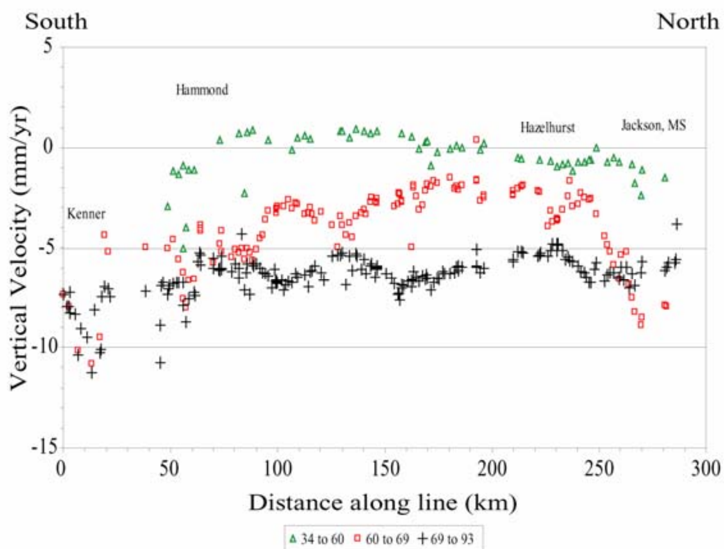

Figure 2. Selected vertical velocity profiles across the south-central United States highlighting areas of historic subsidence; data from Shinkle and Dokka (2004). See Fig. 1 for locations. a) Biloxi, MS to Kenner, LA (near New Orleans). Major episode of subsidence beginning near 1969 is associated with initiation of major movement along Michoud fault in east New Orleans. Aseismic but protracted interval of strain release is suggestive of a "slow earthquake" that ended between 1995 and 2005. b) Subsidence between Alexandria to Creole, LA between 1938-1970. Analysis of groundwater offtake records and fault slips strongly imply a causative relationship in the Lake Charles-Westlake-Sulphur area. These data show that most subsidence and fault motion stopped in the late 1980s when groundwater offtake was abruptly curtailed. Removal of the groundwater effect, however, leaves a residual subsidence that increases steadily towards the south. This suggests that large, ~6km thick, Pleistocene loads that lie offshore have not yet been fully compensated. c) Kenner, LA to Jackson, MS. Some local vee-shaped velocity anomalies are associated with groundwater offtake of shallow aquifers (e.g., near Jackson).

<u>Causes of Subsidence Today</u>

Several natural and human-related processes are known to be causing subsidence in coastal Louisiana today and in the recent geologic past. Almost all previous studies, however, have provided <u>qualitative</u> insights rather than <u>quantitative</u> measurements of actually how much sinking has occurred. It is my opinion that modern subsidence is the integrated effect of multiple natural and anthropomorphic processes that operate at several different spatial and temporal scales. It follows that the motion at any point on the Earth's surface is thus dependent on a unique set of local and regional conditions. A list of these processes is provided below:

- ❖ Natural processes
  - ✓ sediment compaction
  - ✓ sediment consolidation
  - ✓ compaction of semi-lithified rock
  - ✓ Major, regional faulting
  - ✓ Sediment load-induced down-warping
  - ✓ Salt evacuation

- ❖ Human-induced processes
  - ✓ organic sediment decomposition due to drainage projects.
  - ✓ groundwater extraction-compaction of shallow aquitards (clays)
  - ✓ groundwater extraction-compaction of shallow aquifers (sands)
  - ✓ Oil/gas extraction related-compaction of aquitards (clays) – area of subsidence *restricted to only the area of the oil/gas field*
  - ✓ Oil/gas extraction related-compaction of aquifers (sands)
  - ✓ Fault motion-induced by shallow groundwater withdrawal

<u>Measurement of Modern Subsidence</u>

The most comprehensive measurement of modern gulf coast subsidence is based on 1st order geodetic leveling measurements on benchmarks and tidal records published by NOAA Shinkle and Dokka (2004). In an effort to assess the accuracy of the National Spatial Reference System in the region, Shinkle and Dokka computed vertical motions on 2710 benchmarks throughout Louisiana, Mississippi, and coastal areas of Alabama and Florida were indexed to the North American Vertical Datum of 1988 (NAVD88). These authoritative rates demonstrate that modern subsidence has occurred at substantially higher rates than previously thought and that subsidence occurs far beyond the wetlands of the Mississippi River delta (MRD; Figure 1). The data do not support the widely held contention that modern subsidence is the result of merely young sediment compaction/consolidation and human related activities such as oil and gas extraction. The data instead demonstrate that subsidence has multiple natural and human-induced causes that include a large tectonic component and locally, a substantial fault component.

Figure 1 shows some of the vertical velocities computed by Shinkle and Dokka (2004) using NOAA data archives from ~1920-1995. Readers are urged to consult that paper for details on methods and assumptions. This map shows the latest rates at all benchmarks and thus does not represent a single interval of time. In contrast, Figure 2 shows several sections through the region and depicts motions over specific time intervals.

Examination of the spatial distribution of moving benchmarks in the context of their geologic setting provides important insights into processes governing subsidence. First, the most obvious observation is that subsidence occurs far beyond the areal limits of the deltaic plain (Fig. 1 and 2). This is in marked contrast with the prevailing view that considers subsidence to be: 1) concentrated in the modern Holocene delta (MRD) and the alluvial valley of the Mississippi River (MAV); and 2) is primarily the result of local sediment compaction and consolidation. Subsidence rates gradually decline away from the northern and eastern limits of the MRD in Louisiana, reaching zero velocities in northeastern Mississippi and Alabama. Beyond these areas, velocities are positive indicating uplift. North of the MRD (north shore of Lake Pontchartrain), velocities are negative and gradually decline to the north. They peak briefly near the Southern Mississippi "uplift" but subsidence continues far to north along the MAV to near southwestern-most Tennessee (Fig. 1). At the latitude of Vicksburg, an area of subsidence centered at Tallulah, LA, is flanked to the east and west by uplifted areas. This may be due to the weight of the Quaternary sediments in the MAV. To the west, rates remain high across both the coastal Chenier Plain and Cajun Prairie of southwestern Louisiana (Fig. 1). Here, faults and offshore sediment loads are the likely causes.

Previous studies indicate that subsidence continues west along the Texas gulf coast. In southwestern Louisiana, rates increase sharply south of the Tepatate fault system. Relations in the area show a strong association of fault slip to groundwater offtake as a function of time. As the volume of water pumping increased markedly in from the early 1950s through the mid 1980s, so did the motion on local normal faults. Both processes slowed abruptly in the late 1980s. In contrast, much of west-central and northwest Louisiana has been stable.

Second, examination of benchmark velocities as a function of time shows that motions have not been linear through time. This suggests that multiple natural and human-induced processes in the area at work and that some processes have varied through time. Because some of these processes are probably unpredictable, e.g., faulting related strains, human responses to subsidence (e.g., improved groundwater management), eustatic sea level rise, prediction of future subsidence and resultant inundation of areas by the Gulf of Mexico will be uncertain.

The third observation is that subsidence rates based on benchmarks in coastal Louisiana are 2 to 50 times higher than previous estimates developed by state and federal agencies (Fig. 3); long-term geological estimates form part of the basis for the prevailing view on the cause of coastal inundation and land loss (see excellent discussion in Gagliano, 1999). The final observation is that differential motion between benchmarks straddling fault-line scarps or surface projections of subsurface normal faults of the region support the notion that many of these faults are indeed active today and contribute to subsidence and resultant inundation. The Michoud fault of east New Orleans, shown on Figure 2a, is an excellent example.

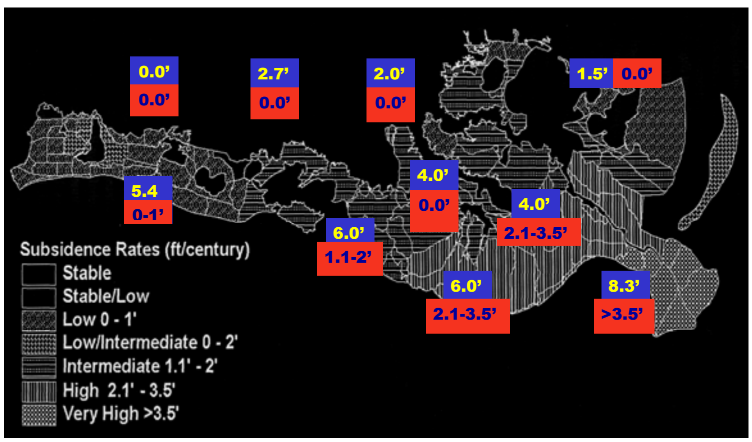

Figure 3. Generalized subsidence rates from wetland areas (Gagliano, 1999) with rates from adjacent land areas implied by geodetic study of Shinkle and Dokka (2004).

<u>The Prognosis for Continued Subsidence in the Near Future</u>

The natural processes causing subsidence will not cease in the next 50-200 years. All natural processes except faulting and load-induced crustal down-warping will likely be constant over this interval. For example, faulting (Fig. 2a, 3) varies through time. When faults are active subsidence increases in magnitude and produces regional effects. When fault motion stops, subsidence slows. Subsidence and resultant land loss at the latitude of New Orleans peaked recently near 1970. When the Michoud fault was active (slipping at ~0.75 inches per year), East New Orleans subsided at rates of nearly 1.75 inches per year. Today, this area subsides at a mere 1 inch per year as the motion on the fault has ceased. Most areas of south Louisiana from Plaquemines to Cameron Parishes have sunk between 1 and 2 feet in the past 20-25 years and faulting can be demonstrated to have played a major if not dominant role in most areas. Faulting, however, cannot be predicted with certainty.

Human-induced causes of subsidence can be stopped by ceasing the offending activity of through mitigation strategies. For example, major subsidence and related effects in the Lake Charles-Westlake-Sulphur area of southwest Louisiana that is associated with primarily industrial groundwater offtake was effectively stopped by switching to surface water sources beginning in the mid-1980s. New Orleans had similar success by changing to river water sources and limiting drainage projects. Large reductions in subsidence were also accomplished in the Houston-Galveston area over the past 30 years through improved management practices; subsidence continues by varying amounts (zero to several centimeters per year) in the region, however, due to continued offtake in some areas and unforeseen natural and natural causes.

<u>Implications of Subsidence for the Long-Term Future of the Gulf Coast;</u>

Several federal agencies (e.g., NOAA, EPA, and USGS) and independent scientists have reached similar conclusions abou the future of Louisiana and other low-lying parts of the Gulf Coast. If the 21st century is a repeat of the 20th century in terms of the combination of subsidence and global sea level rise, then low lying areas from the Mexican border to Pensacola will be below sea level or rendered dangerously vulnerable to hurricanes; unless walls are in place, these areas will be inundated by the Gulf of Mexico. Work by LSU and NOAA researchers validated this scenario in NOAA Technical Report 50. Fig. 4 illustrates the coming inundation if the recent past is similar to the near future. Using the 0.5 inches per year of subsidence seen in the past 50 years and the consensus value of current eustatic rise, most coastal parishes and communities of Louisiana will be inundated in the next 100 years. Hurricanes Rita and Katrina provided brief previews of the coming inundation. In the future instead of short-lived flood and then drainage, the waters will slowly drown the land and remain. <u>There is one CRITICAL caveat, however.</u>

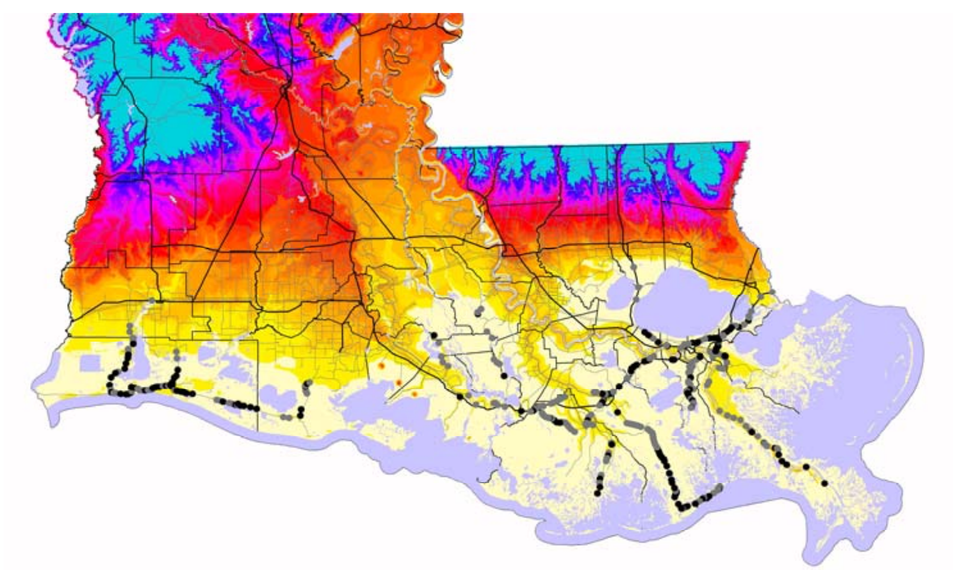

Figure 4. Topography of Louisiana. Cream colored areas lie between +3 feet and sea level. If subsidence and global sea level rise continues, these areas will be at or below sea level sometime by the end of the 21st century. This does not take into consideration any actions by humans or the future behavior of the Mississippi River if it changes course. Black dots, benchmarks that will reach sea level by 2050; gray dots, benchmarks that will reach sea level by 2100.

All predictions of future impacts of changes of nature generally omit how humans will react to this crisis. If we do nothing and the pattern continues, the coast will be gone or rendered too dangerous to live; it is a question of when inundation of unprotected areas will occur. However, it is my opinion that mitigation strategies can be developed to reduce short-term (100-200 years) risks to people and infrastructure, enhance the environment, and create economic development that could transform the state and region (see below).

<u>The Practical Implications of Subsidence for the Immediate Future of the Gulf Coast;</u>

Subsidence has and continues to have major impacts on fundamental aspects of infrastructure and public safety. NOAA told the Congress in 2001 that:

"Cities and cultures are at risk of losing their land and having to relocate. Flooding and sea level rise threaten the coastal region, most of which is only three feet above sea level. Flood plain models and evacuation plans, developed using outdated elevations, put the citizens of the low-lying areas at great risk during heavy rains. The current available geodetic control does not support the state's needs to evaluate and manage the changes in its environment and the impact on its economy and ecosystem. Problems with historic surveys, land movement, and sea level rise have made the current vertical geodetic control in Louisiana obsolete, inaccurate, and unable to ensure safety."

Simply put, if the benchmark is wrong, then everything based on it is inaccurate and may have major negative implications. Examples:

- ✓ Rebuilding New Orleans and communities devastated by hurricane driven storm surge will undoubtedly require upgrading existing levees to new heights that will withstand future events. Without correct data on topography, i.e., the lay of the land, accurate models of storm surge cannot be made by the USACE. **MOST IMPORTANTLY:** We must not merely design the levee that will hold back the waters of a Category 5 hurricane today, we must make that design applicable to 50 years into the future, i.e., the levee must be built to a higher level today to account for future subsidence. We therefore need accurate and precise subsidence rates for planning and continuous monitoring of subsidence to detect unexpected changes during design life of the levee. Similarly, <u>if the vertical control network is off, how will surveyors tell the builders when the levee has been constructed to the final proper grade?</u>
- ✓ Inaccurate elevations on levees and the land preclude the NOAA Storm Surge Modeling Group at the National Hurricane Center (NHC) from making the most accurate storm surge models possible during future hurricanes like Katrina and Rita. These models are used by emergency managers to decide when and where to evacuate. Note: Fortunately, NHC made basic adjustments to their models based on NOAA Technical Report 50 and successfully completed their Mission. The USACE and other also make models for planning purposes and have similar requirements.
- ✓ The viability of all evacuation infrastructure, i.e., roads and bridges, depend on accurate subsidence rates for planning and elevations for construction.
- ✓ FEMA flood maps are tied directly to benchmarks of the vertical control network. Incorrect benchmarks mean inaccurate flood maps, unprotected consumers, and less affective local planning and zoning. More:
    - o Local governments will make bad choices about land use and drainage. Ex., Treatment plants flood and spill toxic materials into neighborhoods.
    - o Consumers buy homes outside of the flood zone only to have them flood during rains.

- A consumer obtains a FEMA flood certificate from surveyor who used a benchmark that was actually lower than the official elevation. It had moved a foot since the last time it was checked.
- A city expands its drainage network based on topography derived from new Lidar technology. The only problem is that the benchmarks used for vertical control were off by differing amounts.

✓ Planning, construction, and monitoring coastal restoration projects are highly dependent on accurate subsidence rates and elevations.

COMMENTS REGARDING HOW SOCIETY CAN EFFECTIVELY COPE WITH SUBSIDENCE

<u>Mitigation strategies</u>

The "disease" leading to coastal land loss in south Louisiana has been attributed generally to processes operating within the marshlands of the Mississippi River delta. The deteriorating wetlands are the most graphic symptom associated with this "disease", and unfortunately, it has been further reasoned that it is also where the disease is located. Thus, hypothesis development, multidisciplinary science integration, and data gathering has been generally limited to the confines of the delta. Mitigation strategies such as outlined in Coast 2050 and by the Louisiana Conservation Authority are therefore designed to treat the symptom. Existing plans lack appreciation of the extent and magnitude of subsidence processes operating today. Subsidence values reported in NOAA Technical Report 50 demonstrate that the ENTIRE coast and environs are subsiding at rates faster and in places than cannot be explained by the paradigm devised by state and federal coastal experts. Mitigation strategies to help wetlands areas do not take into account actual subsidence rates (see www.americaswetlands.org). Although building wetland by mimicking nature (water and sediment diversions) is by itself a good thing to do based on its own merits (e.g., enhancement of various habitats), the plan has been oversold to the public through unsustainable claims of substantial hurricane protection and flood control benefits. Figure 5 illustrates the fallacy of wetlands-centric coastal restoration as the primary solution to Louisiana's coastal woes. Intervention using wetland-centric strategies might initially provide improvement to wetland areas, but it should be obvious from Figure 6 that such a strategy cannot help subsiding land areas of the coast or provide surge protection where people live and work.

A new strategy is needed for the region and it needs to be developed before New Orleans and environs are substantially rebuilt. The strategy selected should reflect the desired outcomes of the local people and the Nation. A well chosen commission of thoughtful listeners and hard questioners could ferret out the possibilities, think about the "unintended consequences" and formulate an effective strategy. To begin this conversation to outline the possibilities, permit me to examine a few of the obvious desired outcomes. If the goal is only a healthy coastal wetland, save the taxpayers money and do NOTHING. Nature will accomplish this quite nicely over time through future flooding and replenishment of subsiding areas. However, use of the Mississippi River as a highway of commerce for the nation will be seriously compromised. Oil production in the deep water gulf will become more expensive as facilities and support centers are moved elsewhere. New Orleans as well as remaining coastal communities will wait for the final storm. Eventually, ever sinking coastal communities will drown or be placed in a position of untenable vulnerability.

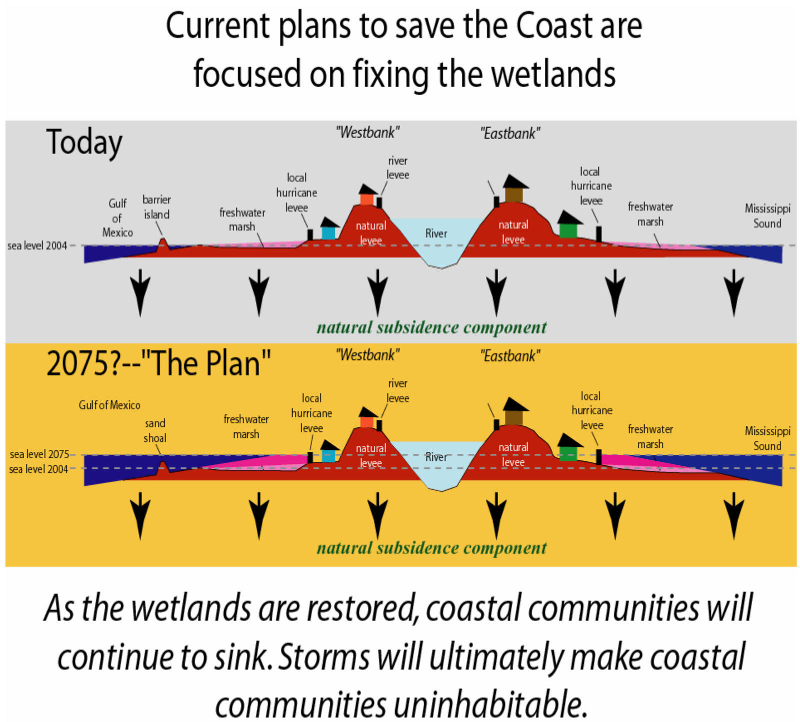

Figure 5. Schematic cross-section of New Orleans area of today and in 2075 if only wetlands restoration programs are implemented. As the ENTIRE coast sinks, the places where people live will be become increasingly more vulnerable to surges over time.

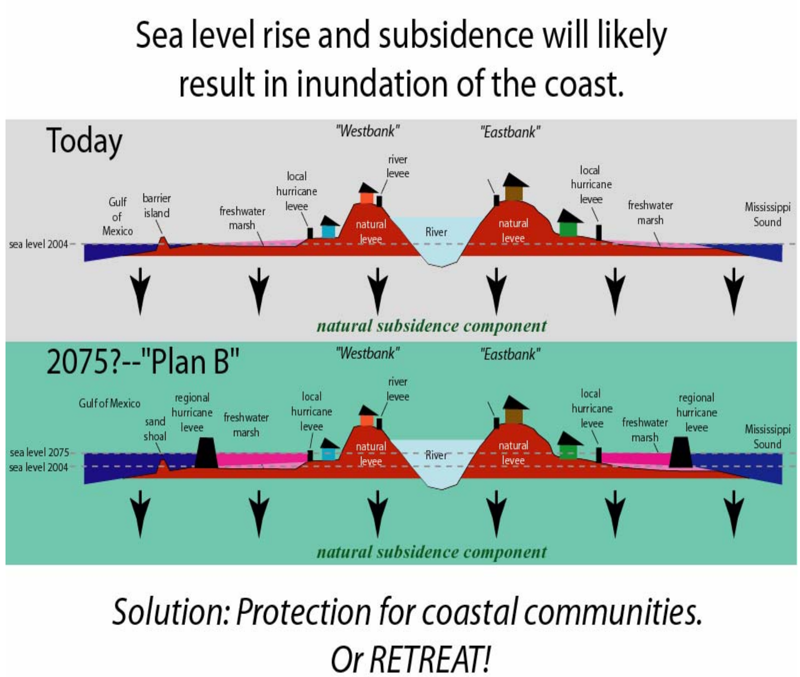

Figure 6. Schematic cross-section of New Orleans area of today and in 2075 if higher levees are built and strategically placed to protect communities and critical infrastructure. Note that wetland areas could also be integrated if planned appropriately.

If our goal is to protect people, property and infrastructure, the choice is clear: higher levees built to meet requirements of the greatest expected storm surge expected over the design life of the project. The essential questions that must be asked and effectively answered are: "Where do we want protection and why? It would be prudent to integrate existing levees of southeastern Louisiana into the plan along with the USACE "Morganza to the Gulf" project. These existing levees need to be higher and made "ocean wave proof". New protection walls will likely be needed to be built along the coast west of Morgan City where none currently exist. Similarly, an effective design needs to be developed along the eastern edge of Lake Pontchartrain to keep out storm surges that might flood Orleans, Jefferson, and St. Charles Parishes from the north. If we as a nation are unwilling to take these steps, we must retreat from the coast.

<u>Action Items that must be accomplished before we rebuild</u>

- ✓ Accurate and sustainable vertical control network. Today there are only 86 points in all of Louisiana that NOAA National Geodetic Survey deems correct. Rebuilding New Orleans and other areas destroyed by the recent hurricanes require accurate vertical control. Acceleration of National Height Modernization Program currently underway by Louisiana State University in partnership with NOAA National Geodetic Survey (http://www.ngs.noaa.gov/heightmod/) is critical if we are prevent future massive mitigation. This could be addressed through funds from FEMA future flood mitigation program. Similar problems exist throughout coastal areas of Texas, Mississippi, and Alabama and require similar attention.

REFERENCES USED IN PREPARATION OF TESTIMONY:

Boesch, D.F., Josselyn, M.N., Mehta, A.J., Morris, J.T., Nuttle, W.K., Simenstad, C.A., and Swift, D.J.P., Scientific assessment of coastal wetland loss, restoration and management in Louisiana, *J. Coast. Res. 10,* Special Issue No. 20, 103 p., 1994.

Dunbar, J.B., L.D. Britsch, and E.B. Kemp, III. Land loss rates: Report 3, Louisiana coastal plain, Technical Report GL-90-2, U.S. Army Corps of Engineers District, New Orleans, La. pp. 28, 1992.

Gagliano, S. M. Faulting, subsidence and land loss in coastal Louisiana, In: Coast 2050: Toward a Sustainable Coastal Louisiana, The Appendices. La. Dept. Nat. Resources. Baton Rouge, La., 1999.

Holdahl S.R., and N. L. Morrison, Regional investigations of vertical crustal movements in the U.S., using precise relevelings and mareograph data, *Tectonophysics 23*, 375-390, 1974.

Roberts, H.H. Dynamic changes of the Holocene Mississippi River Delta Plain: the delta cycle, *J. Coast. Res. 13*, 605-627, 1997.

Saucier, R. T., Geomorphology and Quaternary Geologic History of the Lower Mississippi Valley. U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss. Two volumes, 364 p., 1994.

Shinkle, K., and Dokka, R. K., Rates of vertical displacement at benchmarks in the lower Mississippi Valley and the northern Gulf Coast, NOAA Techn. Report 50, 135 p., 2004

Worrall, D.M., and S. Snelson, Evolution of the northern Gulf of Mexico, with emphasis on Cenozoic growth faulting and the role of salt, The Geology of North America – An overview, Boulder, Geol. Soc. Am., A, p. 97-138, 1989.